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Air Quality Monitoring and On-Site Computer System for Livestock and Poultry Environment Studies

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Abstract. *This article reviews the development of agricultural air quality (AAQ) research on livestock and poultry environments, summarizes various measurement and control devices and the requirements of data acquisition and control (DAC) for comprehensive AAQ studies, and introduces a new system to meet DAC and other requirements. The first experimental AAQ study was reported in 1953. Remarkable progress has been achieved in this research field during the past decades. Studies on livestock and poultry environment expanded from indoor air quality to include pollutant emissions and the subsequent health, environmental, and ecological impacts beyond the farm boundaries. The pollutants of interest included gases, particulate matter (PM), odor, volatile organic compounds (VOC), endotoxins, and microorganisms. During this period the research projects, scales, and boundaries continued to expand significantly. Studies ranged from surveys and short-term measurements to national and international collaborative projects. While much research is still conducted in laboratories and experimental facilities, a growing number of investigations have been carried out in commercial livestock and poultry farms. The development of analytical instruments and computer technologies has facilitated significant changes in the methodologies used in this field. The quantity of data obtained in a single project during AAQ research has increased exponentially, from several gas concentration samples to 2.4 billion data points. The number of measurement variables has also increased from a few to more than 300 at a single monitoring site. A variety of instruments and sensors have been used for on-line, real-time, continuous, and year-round measurements to determine baseline pollutant emissions and test mitigation technologies. New measurement strategies have been developed for multi-point sampling. These advancements in AAQ research have necessitated up-to-date systems to not only acquire data and control sampling locations, but also monitor experimental operation, communicate with researchers, and process post-acquisition signals and post-measurement data. An on-site computer system (OSCS), consisting of DAC hardware, a personal computer, and on-site AAQ research software, is needed to meet these requirements. While various AAQ studies involved similar objectives, implementation of OSCS was often quite variable among projects. Individually developed OSCSs were usually project-specific, and their development was expensive and time-consuming. A new OSCS, with custom-developed software AirDAC, written in LabVIEW, was developed with novel and user-friendly features for wide ranging AAQ research projects. It reduced system development and operational cost, increased measurement reliability and work efficiency, and enhanced quality assurance and quality control in AAQ studies.*

Keywords. *AirDAC, Control, Data acquisition, Instrumentation, LabVIEW, Measurement, Methodology, Software.*

Agricultural air pollution has become an important environmental issue that has attracted growing worldwide attention. Production and emission of aerial pollutants including gases, particulate matter (PM), odor, and volatile organic compounds (VOC) are the main concerns related to increasingly concentrated livestock and poultry production. Agricultural air quality (AAQ) research into these pollutants has seen dramatic changes in terms of monitoring scale, measurement duration, and number of pollutants to be studied simultaneously. Monitoring time has increased to span across animal and bird growth cycles and manure accumulation periods, and to determine seasonal variations in air pollution. Advanced analytical instrumentation and computer technologies have been widely used in laboratory and field AAQ studies.

On-site computer systems (OSCSs), consisting of data acquisition and control (DAC) hardware, personal computers, and custom software, are usually needed in experimental AAQ research with online measurement. While data acquisition (DAQ) remains the basic need, comprehensive AAQ studies also require additional and AAQ-specific features to enhance research efficiency and quality assurance and quality control (QAQC). These features include controlling instruments and multi-point sampling, monitoring experimental operation, communicating with researchers, and processing post-acquisition signals and post-measurement data. Moreover, multi-institutional research projects often require uni-

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form systems and standardized instrumentation and methods for consistency (Phillips et al., 1998; Heber et al., 2008b). Therefore, the OSCS also needs to be flexible so that it can be easily and individually tailored to the particular requirements at each measurement site and can support monitoring plan changes and add-on projects.

There is no commercially available OSCS developed specifically for comprehensive AAQ studies. Although suitable DAC hardware and computers are available commercially, software is not. Thus, the OSCS software is usually custom-developed with project-specific monitoring designs. Individually developed OSCSs have several drawbacks. Firstly, the development of the system, especially the software, is a very time-consuming and expensive process that involves significant time even if it is being adapted from a previous project. A typical AAQ project has limited amounts of time and money budgeted for the development of such a system. Secondly, the resulting software only aims at satisfying the specific project. Therefore, it usually lacks user-friendly flexibility for hardware selection and system configuration to meet the requirements of different projects or add-on studies. Thirdly, these systems usually do not offer advanced features for automation and effective QAQC. This can significantly reduce research quality and lead to additional work during measurement, system maintenance, and post-experimental data processing.

A well-developed OSCS, which not only satisfies the general requirements of AAQ research but also meets the specific constraints of individual projects, can facilitate future research by reducing overall project costs, increasing measurement accuracy, enhancing data completeness and reliability, and improving QAQC. Such a system should provide configurable features and user-friendly interfaces that give it the adaptability to meet changes in research priorities and projects. It should also be based on state-of-the-art AAQ measurement technology. Although some detailed descriptions of individual measurement setups have been published (van't Klooster and Heitlager, 1992; Xin et al., 1994; Berckmans et al., 1998; Heber et al., 2001; Gates et al., 2005), the characteristics of instrumentation and the methodology of designing OSCS for AAQ research have not been studied.

The objectives of this article are to:

- Review the development of AAQ research in livestock and poultry environments.
- Summarize the characteristics and requirements of OSCS in modern AAQ research.
- Introduce the features of a new OSCS for AAQ studies.

Air Quality Research in Livestock and Poultry Environments

Experimental AAQ studies with air pollutant sampling and measurement in livestock and poultry environments were first reported in the early 1950s (Cotterill and Winter, 1953). Remarkable progress has been achieved during the past half century in this research field.

Expanded Research Objectives and Scales

Early AAQ studies in the 1950s and 1960s focused on identifying specific pollutant components (Cotterill and Winter, 1953; Day et al., 1965; Merkel et al., 1969), the effect of ventilation on gas concentrations (Valentine, 1964), and the impact of pollutants on worker and animal health. Quantifying baseline concentrations of indoor pollutants was the primary technical objective of these studies. The pollutants investigated included ammonia (NH_3), hydrogen sulfide (H_2S), carbon dioxide (CO_2), methane (CH_4), alcohols, and carbonyls (table 1).

Since the 1970s, experimental AAQ studies on livestock and poultry environments have expanded from indoor air quality to include pollutant emissions and the subsequent health, environmental, and ecological impacts beyond the farm boundaries. The main objectives of these efforts included: (1) determining pollutant concentrations and baseline emissions related to different animal species at various livestock and poultry facilities; (2) gaining insights into mechanisms of pollutant generation, release, emission, spatial and temporal distribution, and dispersion; and (3) developing and evaluating mitigation technologies. The pollutants of interest were gases, PM (particulate matter), odor, and odorous compounds including VOC, microorganisms, and endotoxins.

In the mid-1970s, research efforts began to determine the characteristics and effects of livestock farms on atmospheric NH_3 concentrations (Luebs et al., 1974) and the emissions of H_2S from swine buildings (Avery et al., 1975). More experimental AAQ studies covering different animal species were reported in the 1980s, especially in Canada (Feddes et al., 1983, 1984; McQuitty et al., 1985; Clark and McQuitty, 1987, 1988; Glennon et al., 1989), the U.S. (Reece et al., 1980; 1981), and Europe (Kroodsma et al., 1993). An OSCS system developed by Feddes and McQuitty (1977) was used in a series of studies in Canada in the 1980s.

Research project scopes and boundaries continued to expand significantly in the 1990s and 2000s. Studies ranged from surveys and short-term measurements (Meyer and Bundy, 1991; Lacey et al., 2003; Gay et al., 2006) to national and international collaborative projects (e.g., Sneath et al., 1997; Wathes et al., 1998; Gates et al., 2005; Heber et al., 2008a, 2008b; Jacobson et al., 2008; Moody et al., 2008). In a northern European multi-country project conducted in the U.K., Germany, The Netherlands, and Denmark, NH_3, CO_2, microorganisms, endotoxins, and PM were measured in 329 animal barns (Wathes et al., 1998). Attention was also given to the impact of AAQ on global climate change, as emissions of greenhouse gases, including CH_4, CO_2, and nitrous oxide (N_2O), were added to the monitoring plans (e.g., Amon et al., 2007; Burns et al., 2008; Ni et al., 2008).

While research in laboratories and experimental facilities has played an important role throughout the history of AAQ research (Cotterill and Winter, 1953; Valentine, 1964; Reece et al., 1981; Braam et al., 1997; Philippe et al., 2007), direct monitoring in commercial animal buildings began in the 1970s (Avery et al., 1975). A growing number of these studies were conducted in the 1980s in Canada with different animal species (Feddes et al., 1983, 1984; McQuitty et al., 1985; Clark and McQuitty, 1987, 1988; Glennon et al., 1989). A commercial pig finishing farm in Belgium was continuously monitored with multi-point sampling for 6.5 months from 1994 to 1995 (Berckmans et al., 1998). In the U.S., air pollutant emissions from eight commercial swine finishing buildings were measured for six months, spanning both hot and cold seasons, from 1997 to 1998 (Heber et al., 2001). The measurement duration increased to one year in a multi-institutional project during 2003-2004 (Heber et al., 2006c;

Table 1. Comparison of selected publications that demonstrate the historical development of AAQ research (1953-1995).

Year[a]	Scale and Facility of Study[b]	Pollutant Studied[c]	Measurement Duration[d]	Sampling and Measurement Method[e]	Reference
1953	1 broiler facility in the U.S., 6 samples (E)	NH_3 (C)	2 days	Acid trap, wet chemistry	Cotterill and Winter (1953)
1963*	One 104-pig finishing barn in the U.S., 2 samples (E)	NH_3, H_2S, CO_2, CH_4 (C)	NA	Cold trap gas collector, glass fiber paper, IR and UV spectroscopy, paper chromatography, pyrolysis	Day et al. (1965)
1964	1 broiler house in the U.K., 490 samples (E)	NH_3 (C)	10 weeks	Acid trap, wet chemistry	Valentine (1964)
1969	1 swine facility in the U.S., 3 samples (E)	CO_2, CH_4, NH_3, H_2S, alcohols, carbonyls, odor (C)	NA	Wet chemistry, gas chromatographs, sniffing	Merkel et al. (1969)
1974	Upwind and downwind from 2 dairies in the U.S. (C)	NH_3 (C)	24 h	Acid trap, wet chemistry	Luebs et al. (1974)
1975	2 farrowing and 4 finishing swine buildings in the U.S., 400 samples (C)	H_2S (C/E)	10 days	Liquid trap, wet chemistry	Avery et al. (1975)
1981	Four 80-broiler environmental chambers in the U.S., 3 trials (E)	NH_3 (C)	Daily for 7 weeks	Gas tubes	Reece et al. (1981)
1982-1983*	3 layer barns in Canada, 6 trials (C)	NH_3, H_2S, CO_2, dust (C/E)	Six 24-h tests	MPS, IR, sulfur analyzer, particle counter	McQuitty et al. (1985)
1983-1984*	6 dairy barns in Canada (C)	NH_3, H_2S, CO_2, dust (C, E)	48 h each barn	Same as McQuitty et al. (1985)	Clark and McQuitty (1987)
1985*	2 turkey barns in Canada (C)	NH_3, H_2S, CO_2, dust (C/E)	1 week each barn	Same as McQuitty et al. (1985)	Feddes and Licsko (1993)
1988	5 pig farrowing rooms in Canada (C)	NH_3, H_2S, CO_2 (C/E)	1 farrowing-to-wean cycle	Same as McQuitty et al. (1985)	Clark and McQuitty (1988)
1989*	1 cubical dairy house in The Netherlands (E)	NH_3 (C/E)	6 months	Sampling chamber, CL	Kroodsma et al. (1993)
1990	200 farrowing pig houses in the U.S. (C)	NH_3 (C)	NA	Gas tubes	Meyer and Bundy (1991)
1992	1 pig setup in Japan (E)	CO_2 (C)	6 tests	IR	Ikeguchi and Nara (1992)
1992-1996*	329 livestock and poultry buildings in the U.K., Germany, The Netherlands, and Denmark (C)	NH_3, CO_2, microorganism, endotoxin, PM	24 h each in winter and summer, 4 replicates for most buildings	MPS, CL, IR, mass oscillator, impaction	Wathes et al. (1998); Phillips et al. (1998)
1994-1995*	4 finishing swine rooms in Belgium, 1 M 12-min data points (C)	NH_3 and CO_2 (C/E)	6.5 months continuous	MPS, CL, IR	Berckmans et al. (1998)
1995	1 finishing swine house in Sweden (E)	NH_3 (C/E)	Eight 5-day experiments	Gas tubes	Andersson (1995)
1995	4 pig compartments in The Netherlands (C)	NH_3 (C/E)	504 compartment-days, continuous	CL	Aarnink et al. (1995)
1995*	1 pig house and 1 broiler house in the U.K. (C)	NH_3 (C/E)	2 months per house, continuous	MPS, CL	Demmers et al. (1999)

[a] Asterisk (*) indicates year when measurement was conducted.
[b] C = commercial; E = experimental; MV = mechanically ventilated; NV = naturally ventilated; TMV = tunnel mechanically ventilated.
[c] C = concentration; C/E = concentration and emission; PM = particulate matter.
[d] NA = not available.
[e] CL = chemiluminesence gas analyzer for NH_3 measurement; EC = electrochemical sensor for NH_3 measurement; FL = ultraviolet fluorescence gas analyzer for H_2S measurement; IR = infrared gas analyzer for CO_2 or multi-gas measurement including NH_3, N_2O, CH_4, etc.; MPS = multi-point sampling using MPS equipment; NMHC = non-methane hydrocarbons; TEOM = tapered element oscillating microbalance.

Hoff et al., 2006; Jacobson et al., 2008). More projects with year-round continuous measurement at commercial farms were conducted in pig barns (Heber et al., 2004; Ni et al., 2008), layer hen barns (Heber et al., 2006a; Zhao et al., 2006; Lim et al., 2007), broiler barns (Burns et al., 2008; Moody et al., 2008), and tom (male) turkey barns (Li et al., 2008). The world's largest AAQ monitoring campaign so far, the ongoing National Air Emission Monitoring Study (NAEMS) is measuring air pollutant emissions continuously for two years at 15 barn monitoring sites on 14 farms in eight states (Heber et al., 2008a, 2008b).

Increased Dataset Size

The quantity of data obtained during a typical AAQ study has increased exponentially in the past five decades. Air pollutant emission studies in the 1950s and 1960s were based on two (Day et al., 1965), three (Merkel et al., 1969), six (Cotterill and Winter, 1953), or 490 (Valentine, 1964) discrete gas concentration samples. Long-term and continuous monitor–

Table 1 (cont'd). Comparison of selected publications that demonstrate the historical development of AAQ research (1996-2009).

Year[a]	Scale and Facility of Study[b]	Pollutant Studied[c]	Measurement Duration[d]	Sampling and Measurement Method[e]	Reference
1996*	4 dairy compartments in The Netherlands (E)	NH_3 (C/E)	Nine periods in 19 weeks	CL	Braam et al. (1997)
1997-1998*	8 finishing swine barns in 2 U.S. states, 155M 20-s data points (C)	NH_3, H_2S, CO_2, PM, odor (C/E)	6 months continuous	MPS, CL, IR, FL, gravimetric, olfactometer	Heber et al. (2001)
2000*	4 TMV broiler houses in the U.S., 720 samples (C)	NH_3, PM (C/E)	10 days from June to Dec.	CL, gravimetric	Lacey et al. (2003)
2002-2003*	2 pig finishing houses in the U.S., 67M 1-min data points (C)	NH_3, CO_2, H_2S, CH_4, NMHC, PM, odor (C/E)	1 year continuous	MPS, CL, IR, FL, TEOM, olfactometer	Heber et al. (2004); Ni et al. (2008)
2003*	10 layer houses in 2 U.S. states, 26,400 30-min data points (C)	NH_3, CO_2 (C/E)	550 house-days	EC, IR	Liang et al. (2005)
2003-2004*	12 barns in 6 U.S. states, 200M 1-min data points (C)	NH_3, CO_2, H_2S, PM, odor (C/E)	1 year continuous	MPS, CL, IR, FL, TEOM, olfactometer	Heber et al. (2006c); Jacobson et al. (2008)
2003-2004*	4 turkey houses in the U.S. (C)	NH_3 (C/E)	One to three 48-h periods in each house	EC	Gay et al. (2006)
2003-2004*	1 pig house in Austria (C)	NH_3, CH_4, N_2O, VOC (C/E)	10 months	FTIR spectrometer, VOC analyzer	Amon et al. (2007)
2004-2008*	3 layer houses in the U.S., 205M 1-min data points (C)	NH_3, CO_2, H_2S, PM, odor (C/E)	6 months in 1 house and three 6-month periods in 2 houses, all continuous	MPS, CL, IR, FL, TEOM, olfactometer	Zhao et al. (2006); Lim et al. (2007)
2006	12 broiler houses in 3 U.S. states (C)	NH_3 (C/E)	At least thirteen 48-h measurements in 1 year	EC	Wheeler et al. (2006)
2006-2007*	2 TMV broiler houses in the U.S., 86M 30-s data points (C)	NH_3, CO_2, CH_4, N_2O, H_2S, NMHC, PM (C/E)	13 months continuous	MPS, IR, FL, hydrocarbon analyzer, TEOM	Moody et al. (2008); Burns et al. (2008)
2007	1 pig finishing room in Belgium (E)	NH_3, N_2O, CH_4, CO_2 (C/E)	6 days per month for 20 months	IR	Philippe et al. (2007)
2007-2008*	4 layer barns and 1 manure compost in 2 U.S. states, 107M 1-min data points (C)	NH_3, CO_2, H_2S, PM, odor (C/E)	1 year continuous	MPS, CL, IR, FL, TEOM, olfactometer	Heber et al. (2006a)
2007-2008*	1 MV turkey barn in the U.S., 83M 30-s data points (C)	NH_3, PM (C/E)	1 year continuous	MPS, no analyzer specified, TEOM	Li et al. (2008)
2007-2009*	35 MV and NV barns and one NV manure shed on 14 farms in 8 U.S. states, 2.4B 1-min data points (C)	NH_3, CO_2, H_2S, CH_4, PM, VOC (C/E)	2 years continuous	MPS, IR, TEOM, GC-MS	Heber et al. (2008a)

[a] Asterisk (*) indicates year when measurement was conducted.
[b] C = commercial; E = experimental; MV = mechanically ventilated; NV = naturally ventilated; TMV = tunnel mechanically ventilated.
[c] C = concentration; C/E = concentration and emission; PM = particulate matter.
[d] NA = not available.
[e] CL = chemiluminesence gas analyzer for NH_3 measurement; EC = electrochemical sensor for NH_3 measurement; FL = ultraviolet fluorescence gas analyzer for H_2S measurement; IR = infrared gas analyzer for CO_2 or multi-gas measurement including NH_3, N_2O, CH_4, etc.; MPS = multi-point sampling using MPS equipment; NMHC = non-methane hydrocarbons; TEOM = tapered element oscillating microbalance.

ing using personal computers and electronic analyzers/sensors enables acquisition of greater amounts of data at higher frequencies. Since the mid-1990s, comprehensive monitoring projects have often been based on continuous measurements of concentration, airflow, and other environmental variables, yielding large quantities of data. A total of one million data points were collected during the field monitoring in 1994-1995 in Belgium, in which data were logged every 12 min (Berckmans et al., 1998). The quantity of data points jumped to 155 million (logging every 20 s) in an 8-barn study in the U.S. from 1997 to 1998 (Heber et al., 2001). The multi-state Aerial Pollutant Emissions from Confined Animal Buildings (APECAB) project (Heber et al., 2006c; Hoff et al., 2006; Jacobson et al., 2008) resulted in 200 million acquired data points, each consisting of a 1-min datum (average of sixty 1-s readings) for one variable, after one year of continuous field measurement. The on-going National Air Emission Monitoring Study (NAEMS) will generate 2.4 billion data points during a 2-year continuous field measurement campaign at 15 barn-monitoring sites on 14 farms (Heber et al., 2008a, 2008b).

The number of measurement variables has also increased significantly. The study of Day et al. (1965) presented only pollutant concentrations. Valentine (1964) published results that had three variables: NH_3 concentration, temperature, and ventilation airflow rate. In the NAEMS barn monitoring effort, the most complex setup among the 15 sites acquires data continuously from more than 300 instruments and sensors. In addition to pollutant concentrations, sensors in the NAEMS project monitor ventilation airflows, indoor air temperatures and relative humidities, weather conditions, animal and worker activities, static pressures, fans, feeders, cooling equipment, lights, manure flushing, and widths of door openings.

Improved Measurement Methodology and Technology

A wide variety of sampling and measurement strategies have been utilized for various AAQ projects over the years. Advances in methodology and technology have also significantly changed the way that AAQ is studied. Sampling chambers for studying odor surface releases designed in the 1970s (Lindvall et al., 1974) have also been used for air sampling in animal buildings (Kroodsma et al., 1993). Micrometeorological methods were developed to determine gas emission at animal farms (Sharpe and Harper, 1999; Cassel et al., 2005). Open-path sampling and measurement using infrared or ultraviolet spectral absorption is a relatively new technology for AAQ research (Shores et al., 2005). Centralized multipoint sampling became a popular method for gas monitoring in animal buildings (e.g., Feddes and McQuitty, 1977; Heber et al., 2001; Moody et al., 2008). This technique applied a single set of analytical instruments to reduce not only the costs of instrumentation, but also the errors that may be introduced among different instruments. This is especially important for comparison studies.

An increasing number of instruments and sensors have either become available or have begun to be used for AAQ projects. For example, there have been 31 different measurement instruments and sensors used for NH_3 measurement at animal facilities (Ni and Heber, 2008). Advances in electronic and computer technologies and their use in measurement devices have revolutionized AAQ research. The advent of different gas analyzers for NH_3, CO_2, H_2S, CH_4, and VOC concentration measurements brought fast, precise, and continuous measurement to reality. Continuous and online measurement of PM has become available in AAQ study since the application of the TEOM (tapered element oscillating microbalance) in this area (Heber et al., 2006b). These technology changes necessitate computer-based and up-to-date systems to acquire high-frequency data, control sampling locations, and perform other automated tasks.

Characteristics of Data Acquisition and Control

Devices

Devices (including instruments, sensors, controllers, etc.) used in AAQ research can be online or offline. Online devices can be connected to the on-site computer while offline devices cannot.

Type 1: Simple Online Measurement Devices

Many sensors used in AAQ research are simple online devices, whose analog or digital outputs can be readily connected to the OSCS. These include thermocouples, relative humidity sensors, certain gas monitors (e.g., infrared carbon dioxide monitor), activity sensors, static pressure sensors, anemometers, and electromagnetic sensing devices (e.g., RPM sensor, current switch, etc.). Their prices are usually in the low to middle range (<$5000).

Type 2: Online Control Devices

Solenoids and relays in AAQ studies are online devices that can be controlled by the OSCS to select sampling air streams and to turn heaters or motors on or off. Their prices are usually <$200.

Type 3: Online-Standalone Measurement Devices

Advanced and more expensive instruments, e.g., gas analyzers and TEOMs, have built-in central processing units and data loggers. They usually have associated software that can be installed in the on-site computer for instrument diagnosis, data downloads, and presentation via serial or ethernet communication. Some of them also offer analog outputs to deliver measurement data to the on-site computer. These instruments can operate alone and/or with the computer. The use of the device software in the on-site computer is often optional.

Type 4: Online-Standalone Devices for Control and Measurement

Gas diluters (e.g., Environics model 4040, Environics, Inc., Tolland, Conn.) are specialized devices that control the delivery of gases used in gas analyzer calibrations, and at the same time monitor the type of gases and their delivery concentrations and flow rates. The Scanivalve (e.g., model DSS24C/MK4, Scanivalve Corp., Liberty Lake, Wash.) is another control and measurement device, which scans pressures at different connection ports. It controls the location to be measured and measures the pressure at that location.

Type 5: Offline-Standalone Measurement Devices

The most sophisticated and expensive instruments in AAQ studies, such as Fourier transform infrared (FTIR) spectrometers, gas chromatograph–mass spectrometers (GC-MS), dynamic olfactometers (e.g., AC'SCENT International Olfactometer, St Croix, Minn.), and fan testers (Gates et al., 2004), are completely independent devices. They require a personal computer that has device-specific software installed to operate the instrument, but do not have analog outputs. Their software offers a complete set of functions for data acquisition, processing, and presentation.

Type 6: Offline Measurement Devices

There are also many offline devices used in AAQ studies that allow direct readings but do not provide electronic output signals. These include gas tubes, regular rotameters, handheld anemometers, psychrometers, and certain gas monitors (e.g., electrochemical gas monitors). Most of these devices are low cost (<$500) because of their simple design.

Type 1 and Type 2 devices are readily connectable to an on-site computer, as are Type 3 devices with analog outputs. Non-analog output Type 3 devices and Type 4 and Type 5 devices require custom software to be integrated into the on-site computer. Type 6 devices cannot be used for computerized data acquisition.

Table 2. Most commonly used online instruments and sensors in AAQ research.

Measurement Purpose	Instrument or Sensor	Signal or Interface
Gas concentration	Gas analyzer, multi-gas analyzer	Analog, serial
PM concentration	Real-time PM monitors	Analog, serial
Temperature	Thermocouple, temperature sensor	Analog
Air humidity	Relative humidity sensor	Analog
Fan on/off status	Vibration sensor, current switch, relay contact	Digital
Fan control signal	Current sensor	Analog
Fan rotational speed	RPM sensor	Pulse
Air velocity	Anemometer	Analog, pulse
Solar radiation	Pyranometer	Analog
Wind direction	Wind vane	Analog
Wind velocity	Anemometer	Analog, pulse
Wind speed/direction	Ultrasonic anemometer	Analog, serial
Atmospheric pressure	Barometer	Analog
Static pressure	Differential pressure sensor	Analog
Animal/worker activity	Activity sensors	Analog
Calibration gases	Gas diluter	Serial

Data Acquisition

There are more than a dozen different types of online devices commonly used in AAQ studies for various purposes (table 2). Each type encompasses several products by different manufacturers. Data acquisition with these devices requires DAQ hardware for analog input, digital input, counter, and serial communication.

Analog Signals

Most online measurement devices provide analog signals that can be readily acquired by analog input DAQ hardware. Analog signal outputs from commercial analyzers and sensors, either as voltage or current, are normally linear. They have fixed or user-selectable signal ranges (e.g., from 0 to 10 VDC or from 4 to 20 mA). Analyzers and sensors with analog outputs also have fixed or user-selectable measurement ranges corresponding to the signal ranges (e.g., 0 VDC = 0 ppm and 10 VDC = 100 ppm for a gas analyzer).

Digital Signals

Some sensors, such as vibration sensors, current switches, or relay contacts, only output low-frequency on/off signals. These sensors are usually low-cost and easy to use. Their signals can be acquired with low-cost digital input DAQ hardware.

Pulse Signals

The outputs of some measurement devices, such as magnetic proximity sensors used to measure fan rotational speed (denoted as RPM sensors) and cup anemometers, are high-frequency (usually several hundred Hz) digital signals or pulses. Counter DAQ hardware and software is typically used to acquire these signals and convert them into frequency data.

Serial Communication

Devices that provide only serial communication (e.g., Innova multi-gas monitor, LumaSense Technologies A/S, Ballerup, Denmark) or provide both analog output and serial communication (e.g., model 81000 ultrasonic anemometer, R.M. Young Co., Traverse City, Mich.) can be connected to the built-in serial ports of the on-site computer or via USB-to-serial converters. Data transferred from these devices via serial communication usually have pre-defined format and time intervals programmed by the device manufacturers. They cannot be readily integrated into the data files generated by the OSCS for AAQ research unless special subprograms are developed and integrated into the main AAQ research software.

Control

Location-shared analyzers and sensors (LSAS) are devices used to measure air samples from different locations. To facilitate the LSAS, sample air from multiple sampling locations is transported in sampling tubing by an automatic control system to these devices. The advantages of LSAS measurement are that errors introduced by different instruments and sensors are minimized, and initial and operating costs of expensive instruments are reduced. The OSCS controls the location, duration, sequence, and frequency of multi-point sampling and measurement. The location numbers and measurement data corresponding to those locations are recorded in the OSCS.

Other devices that are most often controlled online by the OSCS include air sampling line heating tapes, sampling pumps, and cooling fans. Control of these devices, and of the multi-point sampling, usually involves on/off controls by digital output DAC hardware.

Other Requirements

Signal and Data Processing

User-friendly and configurable signal and data processing is a desirable feature in AAQ research. Measurement ranges of some gas and PM instruments with online analog outputs are often adjusted based on seasonal variations of pollutant concentrations in animal facilities. Electronic signals acquired from these devices must be converted and processed based on the adjusted measurement ranges. Moreover, some sensors have unique signal-to-measurement relationships (e.g., activity sensors) or need special real-time data processing algorithms (e.g., wind direction sensor). Automatic post-measurement data processing is also desired in AAQ studies to obtain quick test results and save labor costs.

Monitoring of Experimental System

Comprehensive AAQ studies are usually designed for long-term monitoring, in which the measurement systems are unattended during the majority of the measurement period. An advanced OSCS therefore should feature monitoring of the experimental systems and automatic issuances of alarms or error messages upon detection of any abnormalities.

Monitoring the experimental system involves assessing key environmental and operational parameters that influence the accuracy of the analyzers and the DAQ hardware. Temperature, relative humidity, and pressure are the most commonly monitored environmental parameters. Evaluating all measurement data in real-time and ensuring they are operating within acceptable ranges is an effective way of system monitoring, because a failed sensor or instrument usually outputs data that are outside its normal range.

Real-Time Data Integration

Measurement data from some online-standalone devices can be saved in built-in data loggers and then downloaded to a computer using device-specific software, or logged directly into data files in real-time by the computer via serial communication using software such as Hyper Terminal in Windows. These data are stored under manufacturer-defined formats and data logging intervals with timestamps provided by the instrument's internal clock. The format and data logging intervals are usually different from the OSCS in AAQ studies. The timestamps from the devices and from the PC cannot be guaranteed to match due to clock deviation.

When the data from these devices are a subset of the AAQ measurement data, they must be matched with data from other instruments and sensors during data processing. This can be done manually or with the help of custom-developed computer programs. Differences in timestamps are an error source, and must be carefully monitored and corrected by the researcher.

Experience has shown that when data from all devices are integrated in real-time into a single data file, errors are reduced, along with cost and time of post-measurement data processing. Therefore, all acquired data should be orderly arranged in a single integrated data file whenever possible. Special subprograms may be required for specific devices in order to facilitate this integration.

Communication

Communication discussed in this section is between the OSCS and the researchers. It is critical for QAQC, especially because the OSCS is unattended most of the time. Communication initiated by the OSCS can be visual signs or messages to inform the researchers to perform on-site or remote inspection. It can also be automatic messages or data files sent to the researchers via the internet. Communication initiated by the researchers can be remote login via the internet using commercial software or service to perform inspection and control tasks.

A New On-Site Computer System

To meet the requirements of comprehensive and multiple AAQ research projects since the late 1990s, Purdue University (West Lafayette, Ind.) has developed a new OSCS for both laboratory and field experiments. This system consists of commercial DAC hardware, an on-site computer, and software including the custom-developed AirDAC (fig. 1). It uses commercial software (pcAnywhere, www.symantec.com) or free online services (e.g., gotomypc.com) for remote access and control via internet connection.

The OSCS aims at providing flexibility, user-friendliness, advanced features, and high-level QAQC for various AAQ research and their add-on projects. It has been used in seven laboratory studies and 30 field studies in 13 states in the U.S. since 2000. With continuous upgrade and improvement, including adoption of new DAC hardware, faster computers, and new commercial software, it has developed: (1) capacity for acquiring large numbers of data from up to 500 input channels at 1 Hz, (2) dynamic real-time configuration for analog and digital input-output and signal processing, (3) tabular and graphical displays of all acquired data, (4) measurement system monitoring, (5) integration of stand-alone instruments, (6) active communication with researchers, and (7) automatic post-measurement data processing.

DAC Hardware and On-Site Custom Software

The OSCS uses products from two major DAC hardware manufacturers, National Instruments (NI, Austin, Tex.) and Measurement Computing Corporation (MCC, Norton, Mass.). The system uses one or more banks of FieldPoint (NI) modules connected to the on-site computer via ethernet cables. Each bank can contain up to nine selectable modules

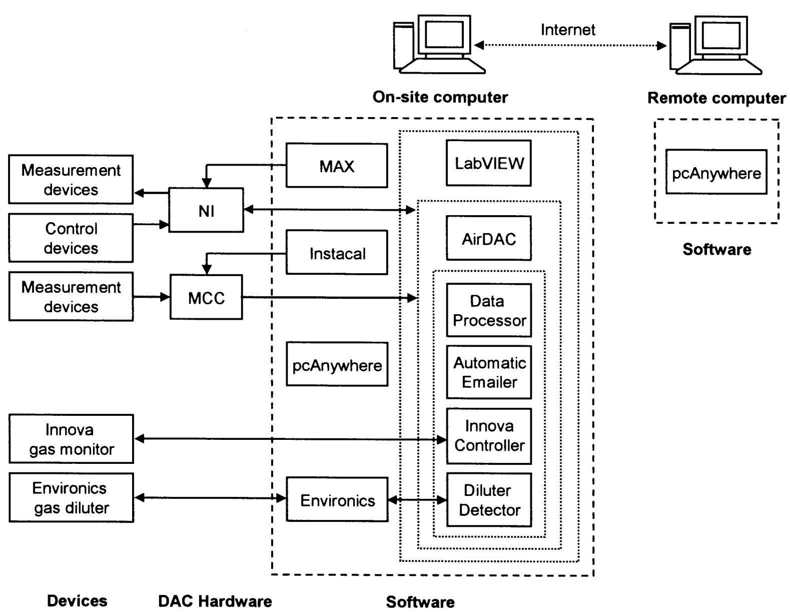

Figure 1. Schematic of the measurement and control devices, the new on-site computer system, and the remote computer for comprehensive agricultural air quality studies.

for analog input, thermocouple input, and digital output. The USB devices used in the OSCS include modules for analog input, digital input, count, and USB-to-serial conversion from MCC and NI. They are relatively low cost and easy to configure. These products can satisfy the general requirements of AAQ studies discussed above.

The analog input hardware includes NI's 16-bit resolution FP-AI-112 or FP-AI-110, each of which has a typical accuracy of ±0.03% of reading, and MCC's USB-1608FS with an accuracy of ±0.04% of reading. They are used to acquire signals from analyzers and sensors that require high accuracy. The 12-bit resolution MCC device miniLab 1008, with an accuracy of ±0.20% of reading, is usually used to acquire analog signal from sensors that do not require high accuracy, e.g., activity sensors. When using FP-AI-112 and miniLab 1008 to acquire analog signals from a gas analyzer of ±1.00% accuracy of full measurement range, the propagation uncertainties are ±1.00% and ±1.02%, respectively. However, AAQ measurement is susceptible to many other errors associated with power supply voltage, electromagnetic interference, changes in temperature, sampling strategy and equipment, temporal and spatial pollutant concentration variations, etc., that have to be taken into account when assessing the uncertainty of the entire measurement system.

The custom software AirDAC is the core of the OSCS. It is written in LabVIEW (NI), which is a graphical development environment with built-in functionality for data acquisition, instrument control, measurement analysis, and data presentation (Elliotta et al., 2007). LabVIEW has been used in some reported AAQ studies (e.g., Boriack et al., 2004; Mutlu et al., 2004; Koziel et al., 2005; Wheeler et al., 2007). AirDAC includes several subprograms, and provides features that allow users to select and configure NI and MCC hardware and perform AAQ-specific tasks (fig. 1).

Signal and Data Processing

Signal and Data Transformation, Correction, and Averaging

Data transformation and processing in AirDAC are based on characteristics of the measurement devices in AAQ studies. Data transformation in AirDAC is for unit conversion and is performed in real-time. AirDAC converts analog signals from the measurement devices to engineering units based on the devices' signal ranges and measurement ranges. For any analyzers and sensors whose converted values needs to be corrected or adjusted using a linear model (e.g., correcting a sensor's outputs based on the sensor's calibration coefficients), AirDAC provides data correction options for each of the data channels with a linear equation. AirDAC acquires signals at 1 Hz, averages the transformed 1 s data readings to 15 s and 60 s means, and saves the mean values in two separate data files.

Activity Sensor Signals

Signals from activity sensors require special transformation because they have an offset voltage. For these sensors, the sensor analog output = offset ± signal. AirDAC subtracts the offset from the signal and takes the absolute value of the signal before performing further data processing.

Digital Sensor Signals

For sensors with digital output signals, AirDAC performs a pre-conversion by multiplying the binary signal by 100 so that the signal represents either 0% or 100% time for the on/off status of the device(s) that the sensor monitors. Using the unit % time allows data to be further averaged without introducing errors compared with using the duration of on/off time in seconds or minutes. For example, 40% in the 60 s data means that the sensor is "on" for 24 s and "off" for 36 s. When two 40% 60 s data are averaged, the "on" time is 40% of 120 s, i.e., 48 s.

Wind Direction Data

Wind direction is a circular function with values between 1° and 360° after data transformation. The wind direction discontinuity at the beginning and end of the scale requires special data processing to compute a valid mean value. A single-pass procedure was recommended by Bennett et al. (1999). The method assumes that the difference between successive wind direction samples is less than 180°; to ensure such, a sampling rate of once per second or greater should be used to compute the scalar mean wind direction. AirDAC has a special wind direction function selectable for each DAQ channel. AirDAC processes the wind direction data on n samples (n = 15 or 60) using the scalar equations (Bennett et al., 1999) to average the samples before they are saved in data files.

Post-Measurement Data Processing

After every midnight, AirDAC automatically processes the previous day's data. It calculates the means of all measured variables with different durations, i.e., every 2, 3, 4, 6, and 24 h. It also processes data from LSAS by separating their sampling locations and extracting valid data after excluding equilibrium time due to sampling line switching. The processed 1 min data and 2 h average data are plotted and presented graphically in an Excel 2007 file.

Post-measurement data processing also includes searching and processing gas analyzer calibration data. The data acquired during calibrations or zero-span checks are picked up from the 15 s raw data files, and the responses of gas analyzers are calculated. The results can be used for studying the gas analyzer's drift over time.

User Interfaces for Dynamic Run-Time Configuration and System Monitoring

AirDAC provides a novel interface for users to easily check all data and configure data transformation and processing during run-time. This is realized with a data display and dynamic run-time configuration (DDRC) table, which contains 17 rows and is resizable from 3 to 500 data columns to satisfy the measurement devices and DAQ hardware in different projects. The table includes 14 editable rows for DAC configurations and three non-editable rows for signal and data display.

AirDAC controls one or two FP-DO-401 modules (NI), each with 16 digital output (DO) channels. Each FP-DO-401 channel can drive up to 2 A at 10 to 30 VDC and is suitable for controlling solenoid valves in a gas sampling system for multi-point sampling and other devices.

AirDAC also provides a user interface for configuring DO control and checking the current status of DO channels in real-time. This is accomplished by a digital output dynamic run-time configuration (DRC) table, which allows users to easily set up and change the sampling location name, duration, sequence, and frequency for multi-point air sampling.

Communication with Automatic E-Mails

AirDAC uses LabVIEW's SMTP feature to send automatic e-mails for measurement alarms, daily data, field notes, and configuration files, and 1 min data notifications. Alarm threshold levels for each measurement variable are user-defined in the data DDRC table. When an alarm occurs, AirDAC sends an e-mail indicating the measurement value, data column, alarm setting, and sampling location number (if requested). When the alarm is cancelled, AirDAC sends another e-mail to notify the same e-mail recipients.

Raw and processed data files of the previous day are e-mailed after midnight to designated recipients. Updated log files or field note files and configuration files (see below) are also e-mailed if they were updated in the previous day. Active notification consists of an e-mail containing 1 min of data at user-selected intervals. The purpose of this feature is to notify researchers that the system is operating while unattended. Not receiving this e-mail is an alert for possible system problems, including internet failure, computer shut-down, software crash, power failure, and lightning damage.

Integration of Standalone Devices

This OSCS integrates two online standalone devices: the Innova photoacoustic multi-gas monitor and the Environics gas diluter.

An Innova Controller subprogram was developed and integrated into AirDAC. The Controller includes a virtual instrument front panel as the interface between the on-site computer and the Innova. It acquires Innova data into AirDAC, which processes the data and saves them in the same files as the data from all other instruments and sensors. This interface also allows remote diagnosis and control of the Innova.

Integration of the gas diluter is made possible via the data log file that is generated by the diluter. A Diluter Detector sub-program was developed in AirDAC to detect the recently saved log files. The Detector reads the contents of the file, interprets the log information, and provides the real-time data to AirDAC. The name of the calibration gas, its actual concentration, and calibration time are saved into AirDAC data files.

Traceable DAC Configuration

Configurations of DAC hardware, data transformation, and data processing are critical information for post-measurement data processing, analysis, and interpretation. During long-term measurements, these configurations are often adjusted or changed for various reasons, e.g., add-on projects, instrument measurement range changes, sampling location/time/frequency changes, data acquisition channel changes, etc. These changes are usually manually recorded, which is time-consuming and can be a source of errors and omissions.

As an important QAQC measure, AirDAC automatically saves all new configurations with a timestamp when they are made and applied. All hardware configuration histories are saved in a text file. All configuration histories related to DAC channel assignment, data transformation and processing, digital output control settings, and e-mail setups are saved in an Excel 2003 or Excel 2007 file. Individual parameters that are changed since the last configuration are colored in the Excel file for easy visual identification.

Summary

Agricultural air quality studies have experienced revolutionary changes in the past half century, especially after the introduction of advanced analytical instruments and personal computers. These changes have called for development of new methodologies and technology to facilitate high-quality and low-cost measurement and system control. On-site computer systems, consisting of DAC hardware, on-site computers, and AAQ research-specific software, are needed for experimental and comprehensive AAQ studies to satisfy not only the basic DAQ task, but also other AAQ-specific tasks.

Online measurement and control devices are preferred in AAQ research for continuous measurement, automation, and real-time monitoring. Most online measurement devices used in comprehensive AAQ studies provide either analog, digital, or pulse signals. They can be readily connected to the OSCS. Other standalone devices need custom programs for integration. Real-time integration of different devices in the OSCS reduces errors, saves time in post-measurement data processing, and should be conducted whenever possible.

System control requirements in comprehensive AAQ studies include regulating air sampling time, location, sequence, and frequency for the LSAS. It also includes control of heating and cooling systems, and pumps for air sampling. All these controls can be realized with DO. In unattended measurement systems, continuous monitoring of operational status is important for AAQ studies.

A new OSCS, which includes the custom-developed and AAQ-specific software AirDAC, is introduced. The system has been used in 37 laboratory and comprehensive field studies in 13 states. It provides configurable and user-friendly interfaces with dynamic real-time configuration, system monitoring, post-measurement data processing, automatic data and alarm delivery, and integration of two standalone devices. This new methodology and technology in AAQ studies shortens development of the measurement systems, enhances project QAQC, increases data quality, and saves time in subsequent data processing.

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Nomenclature

AAQ = agricultural air quality
CL = chemiluminesence
DAC = data acquisition and control
DAQ = data acquisition
DO = digital output
EC = electrochemical
FL = fluorescence
IR = infrared
MPS = multipoint sampling
MV = mechanically ventilated
NMHC = non-methane hydrocarbon
NV = naturally ventilated
OSCS = on-site computer system
PM = particulate matter
QAQC = quality assurance and quality control
TEOM = tapered element oscillating microbalance
TMV = tunnel mechanically ventilated
VOC = volatile organic compounds